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SOUTHEASTERN GEOLOGY

Table of Contents

Vol. 5, No. 2

1964

1. Isolated Fault Scarps on the Continental Slope off Southwest Florida

John W. Kofoed
G. F. Jordan 69

2. Pleistocene "Coquina" at 20th Avenue South Myrtle Beach, South Carolina, and other Similar Deposits

Jules R. Du Bar
Henry S. Johnson, Jr. . . 80

3. Chemical Analyses of Rocks of the Carolina Slate Belt

James Robert Butler . . . 103

4. Filled Submarine Spring Vents in Cretaceous Rocks of Alabama

William F. Tanner 115

ISOLATED FAULT SCARPS ON THE CONTINENTAL SLOPE OFF SOUTHWEST FLORIDA

by

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ABSTRACT

The upper continental slope off the west coast of Florida from Pourtales Terrace to DeSoto Canyon is regular and gently sloping. Details of the bathymetry in this area that do not appear on published nautical charts are given, the most striking of which is located approximately 45 miles west of Dry Tortugas, Florida. Here isolated escarpments, interpreted as step faults, form a terrace on the otherwise regular slope. This terrace is oriented normal to the strike of the continental slope thus forming a bold topographic feature.

INTRODUCTION

By virtue of the continuing hydrographic program of the U. S. Coast and Geodetic Survey over the continental shelf and slope of the United States basic data are provided for developing detailed bathymetric charts. As a result of these accurate and detailed surveys Jordan (1951, 1952) and Jordan and Stewart (1959, 1961) have reported on the submarine physiography of a large portion of the continental terrace off the west and south coast of Florida from Pensacola to the Florida Keys.

The present report describes in detail a feature located between the areas of the two most recent studies on the continental slope off southwest Florida and in the western Straits of Florida. It is the purpose of this paper to point out and describe isolated fault scarps on the upper continental slope.

The study area (Figure 1) is approximately 20 nautical miles on a side, centered at latitude 24°35'N. and longitude 83°45'W., which is about 45 miles west of Dry Tortugas, and 220 nautical miles southwest of Tampa.

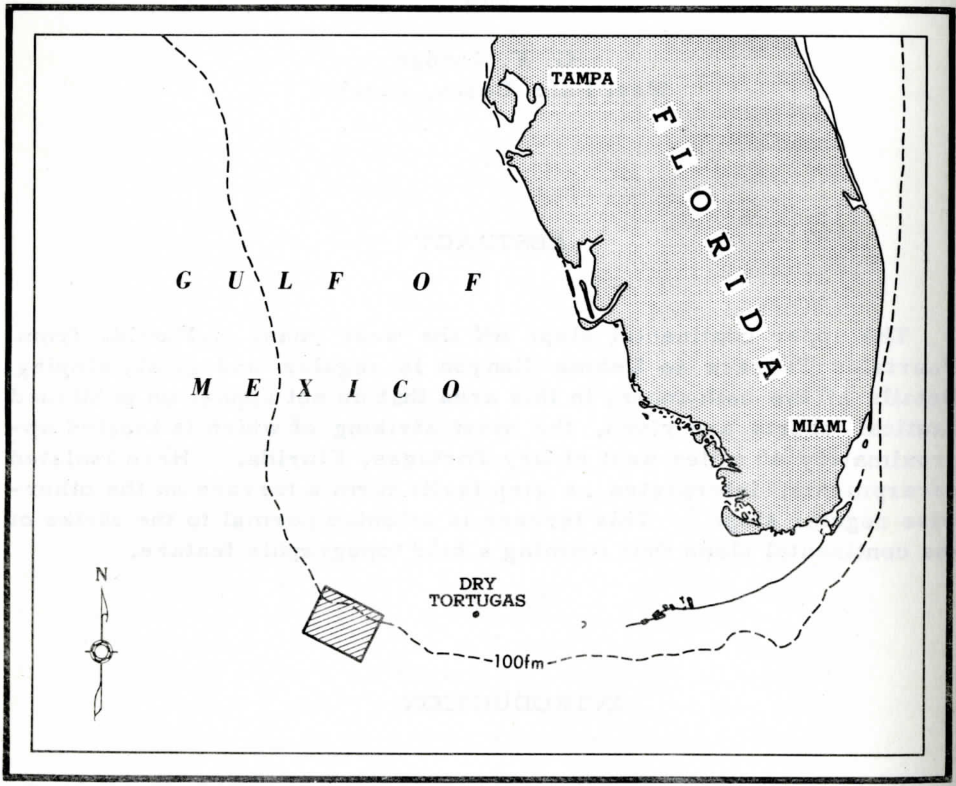

Figure 1. Index map showing the general location of a fault terrace relative to the Florida Platform.

In contrast to the continental terrace of the north and northwest Gulf of Mexico where geologic interest and research has flourished, almost all of the previous work on the submarine topography of the continental terrace in the eastern Gulf of Mexico has been on a relatively small scale and consequently, many of the interesting and detailed aspects have been neglected with the exception of the studies noted above. At the present time the shelf sediment descriptions are for the most part restricted to bottom notations on the hydrographic survey smooth sheets. The gross character of the Florida Platform has been previously discussed by Vaughan (1910), Pressler (1947), Ewing, et al (1958), and others.

The hydrographic surveys used in this study were made as part of a project covering the eastern Gulf of Mexico and the Straits of Florida. The field work was done during the 1952, 1953, 1954 field seasons on the USC&GS ship Hydrographer. Hydrographic surveying as used in this report is defined as, ". . .that branch of physical oceanography employed to define the configuration of the bottom of oceans and navigable waters of lakes, rivers, and harbors" (Jeffers, 1960).

The writers wish to acknowledge the support of the Survey and also the helpful suggestions and criticisms of Orrin H. Pilkey of the University of Georgia Marine Institute.

BATHYMETRY

The continental slope along west and southwest Florida extends from 100 fathoms to depths exceeding 1800 fathoms. Beginning at approximately 600 fathoms, the lower portion of the slope is formed by a major escarpment which extends along west Florida. This escarpment was described by Jordan (1951) and Jordan and Stewart (1959). The upper continental slope ranges in depths of 100 to 600 fathoms. From the western end of the Pourtales Terrace in the Straits of Florida, westward and northward around the Florida Platform the upper slope is relatively smooth and featureless, particularly north of 27°N. latitude where it is very broad and smoothly sloping.

The smoothness and continuity south of 27° N. is interrupted by long breaks in slope which Jordan and Stewart (1959) interpreted as the surface expression of minor faults parallel to the major fault forming the Florida Escarpment.

A striking exception to the character and configuration of the upper slope is the fault terrace shown in Figure 2 normal to the strike of the slope and linear features along the slope. Heretofore unnamed, Tortugas Terrace is proposed as a name for this feature after Dry Tortugas, a group of small islands in the Gulf of Mexico 65 miles west of Key West, Florida. The scarps define a rectangular segment

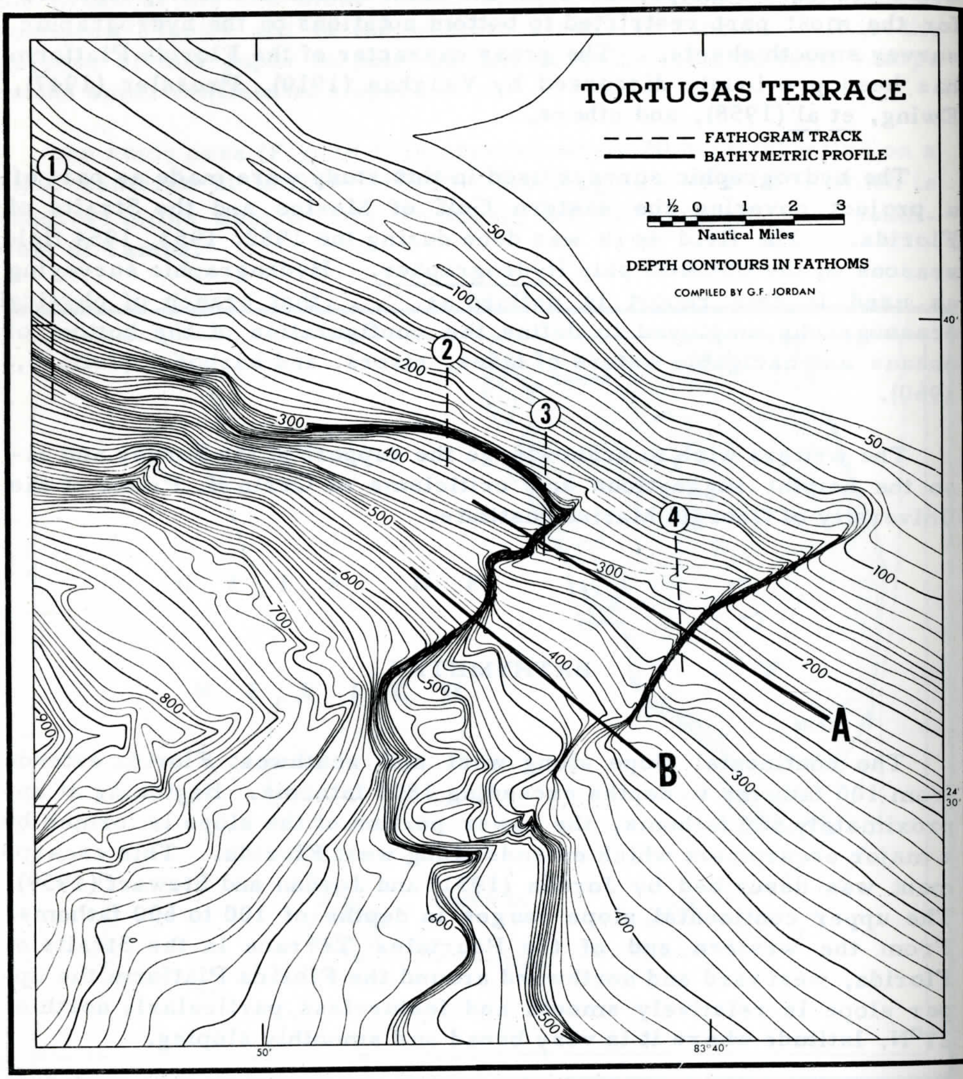

Figure 2. A bathymetric chart of a fault terrace on the continental slope off southwest Florida with locations of fathogram and bathymetric profiles of Figures 3 and 4 respectively.

of the sea floor roughly 4 by 8 nautical miles orientated northeast-southwest. Depths over the surface range from 100 to 500 fathoms over the 32 square nautical mile area. Bordering the terrace on the west is a 90 fathom scarp dipping 45 to 49 degrees; to the east a 13 to 27 degree scarp rises 80 to 90 fathoms up to the undisturbed portion of the upper slope. To the south a more gentle and arcuate scarp slopes 6 to 13 degrees for 100 fathoms. The northern extent of the terrace is not clearly defined.

Profiles A and B (Figure 3) illustrate the relationship and relative dimensions of the scarps to the terrace and show the terrace is horizontal along a NW-SE profile or traverse. The change in the degree of slope from 27 to 13 degrees on the east scarp is attributed to slumping. On the basis of the profiles of Figure 3 and the bathymetry of Figure 2 it appears there is little if any sediment deposition at the base of the two scarps. This is attested to by the presence of a small trough along the base of the east scarp, and the distinct and abrupt change in profile at the base of the other scarps. This is possible due to water movement along the scarp face or a very recent age for the feature. Unfortunately, however, data on water circulation in this area are not available.

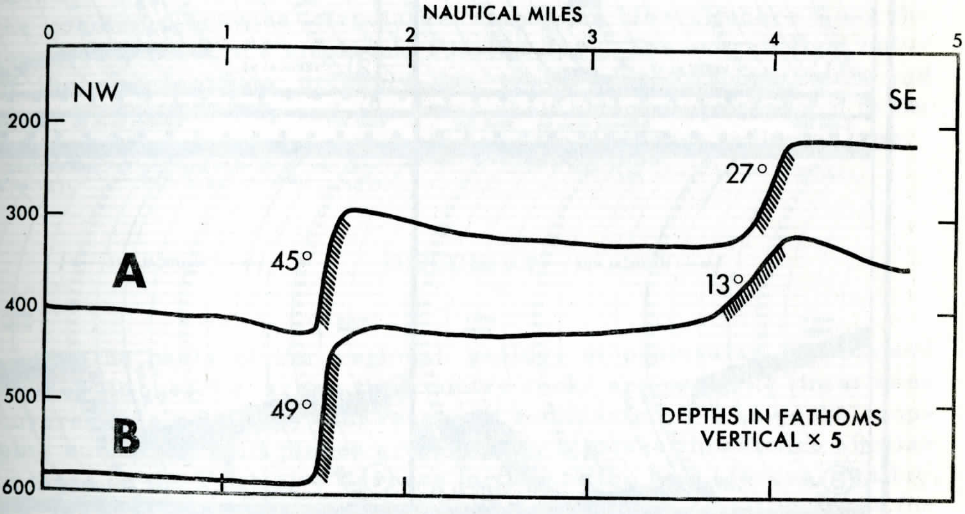

Figure 3. Bathymetric profiles across the terrace showing the scarps relative to the terrace. Depths are shown in fathoms.

The fathograms in Figure 4 are typical profiles over the various scarps in the area. All these fathograms are oblique to the strike of the scarps and therefore do not show the true-dip.

Immediately west of the lower scarp in approximately 680 fathoms is the head of a large valley extending down the continental slope to depths exceeding 1900 fathoms at the mouth. The valley axis is essentially straight and has the same general trend as the fault scarps in Figure 2. At the valley head the abrupt change in the trends of the

700, 750, 800, and 850 fathom contours gives the appearance of two gently sloping intersecting surfaces. The line of intersection is made by connecting the points of abrupt change in trend of the contours noted above.

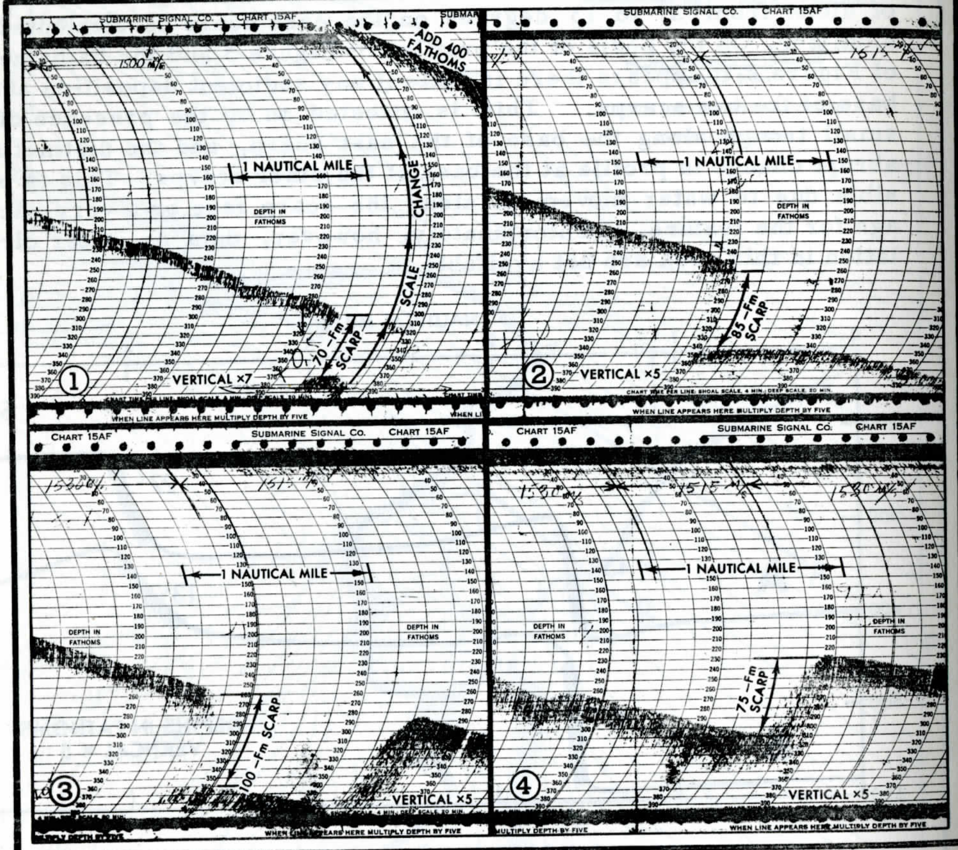

Figure 4. Fathograms across several scarps in the study area. The tracks are not normal to the strike of the scarps (See Figure 2). Depths are shown in fathoms.

SEDIMENTS

Sediment descriptions are based on the bottom notations recorded in the field in support of the hydrographic surveys. As many as possible were taken from the recent survey sheet, however, some are from the old sheets of the 1870's. The subjective nature of these notations is recognized but they are believed to be suitable for a discussion of gross sediment characteristics.

Above the 150 fathom contour the bottom consists of sand and broken shell with coral fragments occurring locally. In the embayment formed by the two intersecting scarps fine grey mud occurs which probably extends downslope into the deeper water. Fine white calcareous sand and shell fragments are noted over the fault terrace and the upper continental slope to the east. The sand is probably all calcareous, having been spread across the shelf by the Gulf currents and hurricanes, the latter undoubtedly being the prime factor as southern Florida is susceptible to these storms. Almost all of the hurricanes on record in southern Florida have come from a direction between 135 and 245 degrees. As these storms approach the Keys the counter-clockwise circulation trends to blow offshore along the lower west coast of Florida and Florida Bay. The overall light color of the sediments is probably due to the white carbonate silts and clays of Florida Bay and the inner shelf being swept seaward to the outer shelf areas where carbonates are the dominant sediment type.

DISCUSSION

On the basis of the regional geology of peninsular Florida and studies in nearby areas the country rocks are probably limestones covered by a relatively thin veneer of sediments. The rocks cropping out on the fault planes are probably Miocene limestones similar to those on the Pourtales Terrace further to the east (Jordan, Malloy, and Kofoed, in preparation). Presently there are tentative plans for subbottom profiling and sediment coring in this area which may aid in a more detailed interpretation of this bottom feature.

In contrast to the relatively gently sloping and featureless upper continental slope of west Florida, this fault terrace is a unique feature because the fault scarps are so clearly defined and are orientated perpendicular to the slope. This is the only feature noted so far on the upper continental slope of west Florida with this attitude. It appears that the scarps are normal fault planes along which displacement has produced a step fault, Tortugas Terrace. The vertical displacement averages 720 feet on the west fault and 240 feet on the east. To further substantiate the fault origin of the terrace an overlay was made on which the soundings were decreased in value equal to the vertical difference between the sea floor on either side of the scarps. The area east of the terrace was assumed to be undisturbed and was used as a reference. The depths on the terrace were decreased by the difference in depths between the top and bottom of the scarp. The depths in the embayment to the west of the lower scarp were decreased by the difference in depth between the area east of the terrace and the depths at the base of the lower scarp. The result of this reconstruction was a gently sloping featureless surface over the terrace and embayment coinciding with the undisturbed continental slope to the east and northwest. The writers believe this is indicative of down-on-the-west faulting and that the terrace is in fact a step fault.

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PLEISTOCENE "COQUINA" AT 20TH AVENUE SOUTH

MYRTLE BEACH, SOUTH CAROLINA, AND

OTHER SIMILAR DEPOSITS

by

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and

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Division of Geology
South Carolina State Development Board

ABSTRACT

Pleistocene "coquina" crops out on the beach at 20th Avenue South, Myrtle Beach, South Carolina. The presence of cobbles, small boulders, and well developed festoon cross-bedding indicates deposition by a strong current that flowed southwestward parallel to the Sangamonian Myrtle Beach Barrier Bar. Fossil content, position of the "coquina" relative to the Myrtle Beach Barrier Bar, relation to present day sea level, and similarity to other "coquina" deposits along the Carolina coast indicate deposition most probably took place during Sangamonian time.

Because of the lithologic variability of the deposits studied, the authors have used the term coquina only as a general field term. The current vagueness of the term also argues against its use in any formal lithologic sense.

Pleistocene "coquina" deposits of the Carolinas appear to group in three general types. These are (1) longshore current deposits on the seaward edge of barrier bars, (2) storm or surf zone accumulations in bars, and (3) inlet deposits.

Longshore "coquina" deposits are typified by the outcrops at 20th

Avenue South, Myrtle Beach, and at Fort Fisher, North Carolina. Where exposed above water these deposits characteristically exhibit well developed festoon cross-bedding. The parts of the outcrops that are only rarely above water have a rough, knobby surface and appear structureless. These parts are thought to have formed under similar conditions, however, and may well possess the same sedimentary structures.

Cementation of the "coquina" deposits probably took place at a time of lower sea level, when weathering of the shelly sands caused solution and redeposition of calcium carbonate.

Other "coquina" deposits may be present in association with ancient offshore bars at higher levels in the Coastal Plain.

INTRODUCTION

Isolated patches of Pleistocene "coquina" have been reported along the coastal areas of North and South Carolina by several authors (Tuomey, 1848; Pugh, 1906; Stevenson, 1912; Cooke, 1936; Richards, 1936 and 1950; and Wells and Richards, 1962). In more recent years these deposits generally have been thought to be similar in appearance to the Anastasia Coquina of northeastern Florida and probably of the same age (i.e., Sangamonian).

Cooke (1936, p. 153) and Richards (1936, p. 1638) each reported an exposure of "coquina" on the beach at Myrtle Beach, Horry County, South Carolina. Tuomey's earlier mention (1848, p. 187) of calcium carbonate cemented rock composed of shells mixed with pebbles designates only an exposure on the beach "On the coast of Horry District ..." but in all probability refers to the same Myrtle Beach deposit or deposits.

The "coquina" studied by the authors crops out on the beach at Myrtle Beach at the seaward end of 20th Avenue South (Fig. 1). It is not known whether this is the exposure noted by Cooke and Richards inasmuch as another "coquina" bed is exposed at very low tides on the beach to the north opposite 2nd Avenue North.

It is the purpose of this paper to describe the general characteristics of the "coquina" outcrop at 20th Avenue South, Myrtle Beach; to discuss its geologic setting and probable origin; and briefly to explore its relationship with similar occurrences along the coast of the Carolinas.

Field investigations of the Myrtle Beach "coquina" and other similar deposits in North and South Carolina were made by the authors in the summer of 1962 and the fall of 1963.

ACKNOWLEDGMENTS

This project was supported in part through a grant to the senior author from the National Science Foundation and in part by the Division of Geology, South Carolina State Development Board.

The authors were assisted in part of the field work by James F. Fowler of Houston, Texas, and Hobart W. C. Furbunch of Myrtle Beach, South Carolina.

G. Robert Lunz and C. B. Stevens of Bears Bluff Laboratories, Wadmalaw Island, South Carolina, and A. J. Willis of the South Carolina Division of Commercial Fisheries provided information on "coquina" just off Edisto Beach, South Carolina, and also supplied a specimen of the rock.

Ben Heyward of the South Carolina Division of Commercial Fisheries provided specimens and additional information on "coquina" from Murrells Inlet, South Carolina.

Frank M. Beckham, Department of Parks and Recreation, Myrtle Beach, South Carolina, provided a jeep used by the authors in searching for "coquina" deposits along the beach in the Myrtle Beach area.

Charles T. Tilghman, Ocean Drive Beach, South Carolina, was helpful to the authors in their search for previously reported deposits of "coquina" at Windy

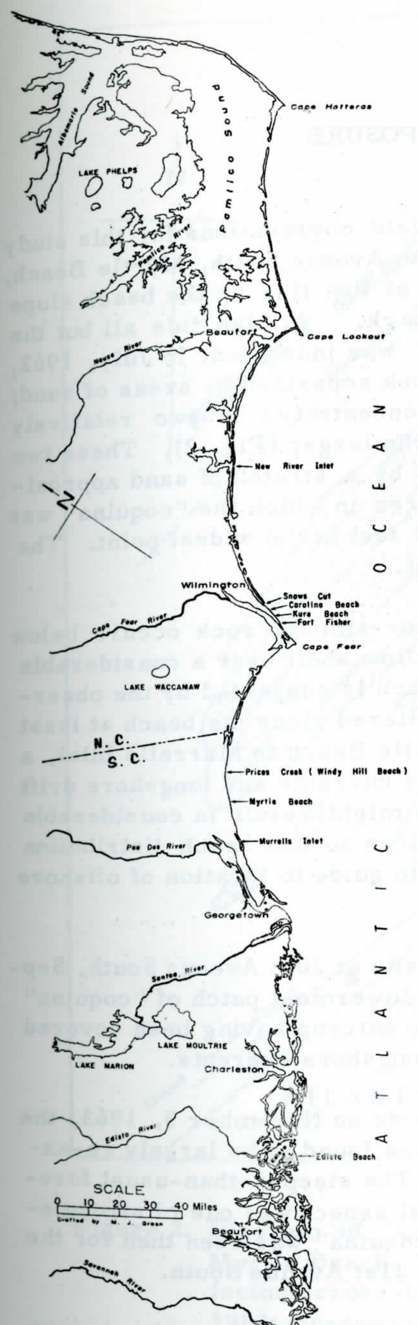

Fig. I. Index map showing location of Myrtle Beach "coquina" and other similar deposits in the Carolinas.

Hill Beach, South Carolina, and on nearby Prices Creek.

NATURE OF EXPOSURE

In July, 1962, when most of the field observations for this study were made, the "coquina" outcrop at 20th Avenue South, Myrtle Beach, extended from below the water's edge at low tide up the beach slope approximately to the mean high tide mark. At high tide all but the highest, innermost edge of the "coquina" was inundated. In July, 1962, there were numerous patches of the rock separated by areas of sand; however, most of the "coquina" was concentrated in two relatively large outcrops with the inner one being the larger (Fig. 2). These two main outcrop patches were separated by a stretch of sand approximately 40 feet in width. The entire area in which the "coquina" was exposed was 365 feet in length and 72 feet at the widest point. The maximum exposed thickness was 3.5 feet.

The possibility that the "coquina" or similar rock occurs below low tide level in the surf and on the shallow shelf over a considerable distance along the coast near Myrtle Beach is suggested by the observation that pieces of the rock are scattered along the beach at least from a point opposite the center of Myrtle Beach to Murrells Inlet, a distance of 13 miles (Fig. 1). Longshore currents and longshore drift resulting from oblique wash of waves might result in considerable transportation of at least the smaller pieces so that beach distribution of erosion debris may not be a reliable guide to location of offshore deposits.

When the junior author visited the site at 20th Avenue South, September 24 and October 5, 1963, only the lowermost patch of "coquina" was still exposed, the larger part of the outcrop having been covered by sands carried from the northeast by longshore currents.

When visited by the authors at low tide on November 3, 1963, the "coquina" outcrop at 20th Avenue South was found to be largely re-excavated and noticeably deteriorated. The steeper-than-usual foreshore had an 8^{o} slope, and the general aspect was one of strong erosion. Another, smaller outcrop of "coquina" was seen then for the first time at the low water mark at about 21st Avenue South.

The several visits by the authors to the outcrop at 20th Avenue South have served to focus attention on the constant conflict between

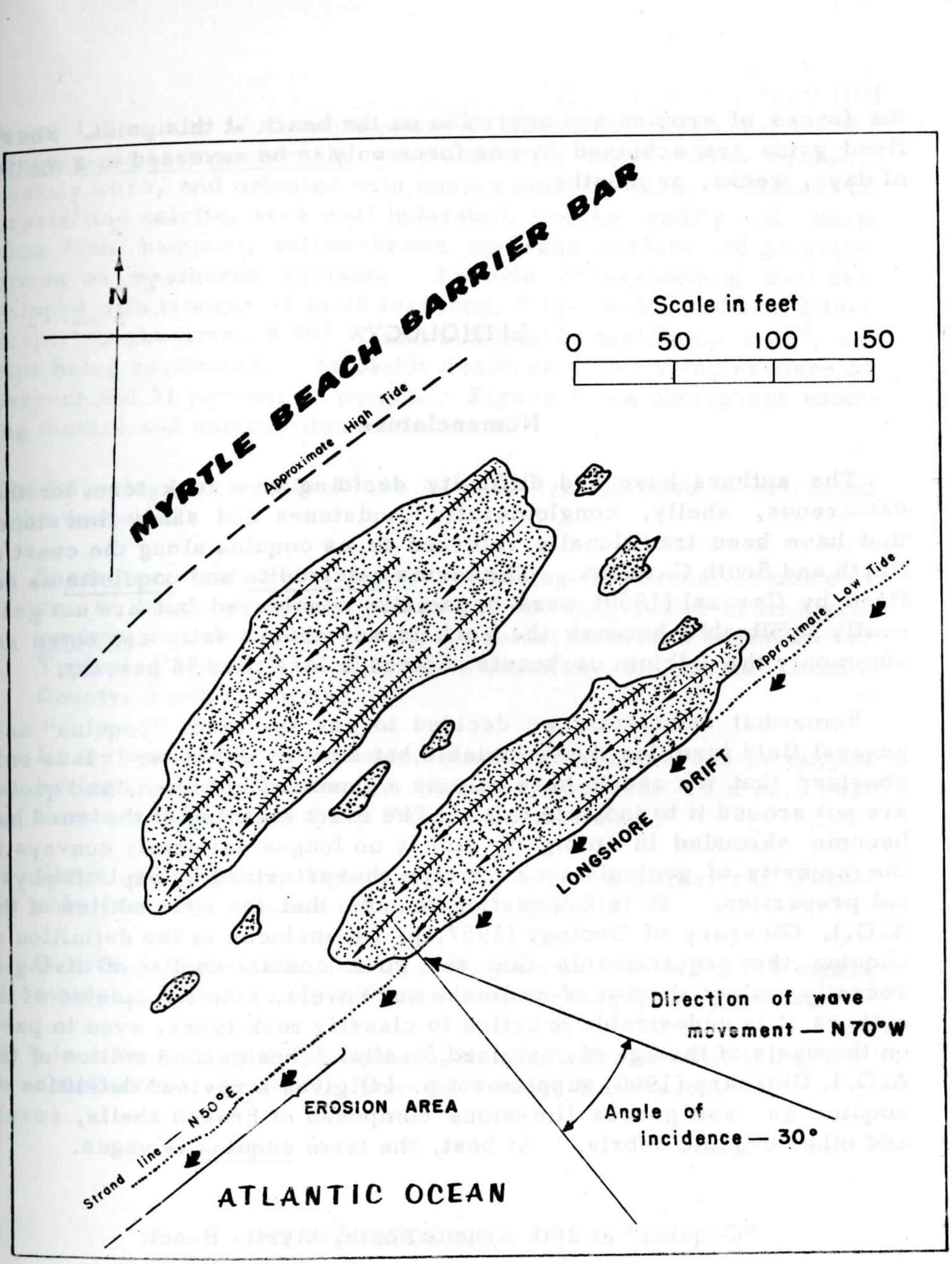

Figure 2. Diagram of "coquina" outcrop area, 20th Avenue South, Myrtle Beach, South Carolina. Arrows show plunge of festoon cross-beds. (Rock exposures as they were in July, 1962; oceanographic conditions observed September 24, 1963.)

the forces of erosion and accretion on the beach at this point. Short-lived gains are achieved by one force only to be reversed in a matter of days, weeks, or months.

LITHOLOGY

Nomenclature

The authors have had difficulty deciding on a rock term for the calcareous, shelly, conglomeratic sandstones and sandy limestones that have been traditionally referred to as coquina along the coast of North and South Carolina. The terms calcirudite and coquinite as defined by Carozzi (1960) were especially considered but are not generally applicable because the rock is not always fully cemented and commonly the calcium carbonate content is less than 50 percent.

Somewhat reluctantly we decided to use the term "coquina" as a general field term for these variable but similar deposits. It is emphasized that we use it here only as a general field term, and quotes are put around it to indicate this. The exact meaning of the word has become shrouded in ambiguity and it no longer uniformly conveys to the majority of geologists a rock type characterized by explicit physical properties. It is interesting to note that the first edition of the A.G.I. Glossary of Geology (1957, p. 64) includes in the definition of coquina the requirements that the rock contain shells of living or recently extinct species of mollusks and corals. In the opinion of the authors it is undesirable practice to classify rock types, even in part, on the basis of the age of contained fossils. The second edition of the A.G.I. Glossary (1960, supplement p. 14) gives a revised definition of coquina as "soft porous limestone composed of broken shells, corals and other organic debris." At best, the term coquina is vague.

"Coquina" at 20th Avenue South, Myrtle Beach

A description of the "coquina" at 20th Avenue South, Myrtle Beach, is as follows:

Sand fraction fine to coarse, primarily quartz, 2-3 percent black phosphate grains, all grains subangular to subrounded, clear to heavily frosted; pebbles, cobbles, and boulders up to 25 centimeters in diameter, all subrounded to rounded, comprised of sandstone, quartz, quartzite, chert, and limestone. Shells range from 1.0 mm to 12.5 centimeters in diameter; large valves of Mercenaria campechiensis very common; most valves broken, heavily worn, and oriented with convex sides upward. Cement of crystalline calcite, rock well indurated, breaks readily with sharp blow from hammer; yellow-brown on fresh surface and grayish-brown on weathered surface. Festoon cross-bedding well developed with troughs 10 to 20 feet long, 5 feet wide, and 1 to 2 feet deep; troughs trend S 50° W and individual beds dip up to 22°, all dips being southward. Insoluble residues of two samples were 65 percent and 51 percent by weight. Figure 3 is a photograph showing texture and composition of the rock.

The following descriptions are of five typical cobbles extracted from the "coquina":

1. Sandstone, very calcareous; containing 5 percent or more of coarse black phosphate grains and one large valve of Exogyra costata; rounded; olive-brown in color; 10 x 12.5 centimeters. Typical Peedee (Cretaceous) Formation of coastal Horry County, South Carolina.

2. Limestone, very phosphatic, black; with numerous pelecypod borings 1-2 centimeters in diameter; rounded; 7.5 x 12.5 centimeters. Probably from Peedee Formation.

3. Chert, subangular, light gray; 3.0 x 5.0 centimeters. Probably from Pleistocene terrace-plain gravels.

4. Quartz or quartzite, subrounded, pale yellow; 5.0 x 7.5 centimeters. Probably from Pleistocene terrace-plain gravels.

5. Limestone, slightly phosphatic, sandy, olive-brown; 3.0 x 5.0 centimeters. Probably from the Peedee Formation.

CROSS-BEDDING

Well developed festoon cross-bedding is the dominant sedimentary structure in the "coquina" at 20th Avenue South, Myrtle Beach (Fig. 4). The troughs are 1 to 2 feet deep, about 5 feet wide, and 10 to 20 feet long. Trough axes vary in trend from S 45° W to S 55° W and average about S 50° W. Dips of individual bedding planes are up to 22° in a southward direction.

Figure 3. "Coquina", 20th Avenue South, Myrtle Beach, South Carolina. (Rollei lens cover for scale.)

Festoon or trough cross-stratification of this type has been well described by Stokes (1953), Pettijohn (1957, p. 169), and Harms et al. (1963). Observations made by the junior author during several years of investigating uranium deposits in fluvial sandstones of Triassic and Jurassic age on the Colorado Plateau bear out the general consensus that festoon cross-beds are caused by fairly strong currents and that they are excellent current direction indicators.

The well developed festoon cross-bedding in the "coquina" at 20th Avenue South, Myrtle Beach, is therefore interpreted as indicating deposition by a strong current that flowed approximately S 50° W.

During a period of lower than normal tide on November 3, 1963, it was noted that the seawardmost part of the "coquina" outcrop at 20th Avenue South, a part not normally exposed above water, showed no cross-bedding, presenting instead a rough, knobby surface that appeared to be without preferred layering or orientation of any kind. There is no evidence, however, that the apparently structureless "coquina" is anything other than part of the same deposit which shows such well developed festoon cross-bedding higher on the beach. The presence of large cobbles in the apparently structureless "coquina" is strong evidence that it also was deposited by strong currents. It is not certain whether the apparently structureless nature here is due to absence of cross-bedding or to lack of subaerial erosion which may etch the rock and bring its structure into noticeable relief.

Figure 4. Festoon cross-bedding in "coquina" at 20th Avenue South, Myrtle Beach. (Sixty-five pound friendly Airedale for scale.)

FAUNA

The fauna in the "coquina" at 20th Avenue South, Myrtle Beach, consists predominantly of pelecypod valves but includes some gastropod shells and echinoid spines. A few corals and other fossil types are probably included but were not observed by the authors.

Numerous thick-shelled species are included in the fauna, but there is also a significant quanitity of small, fragile-shelled forms. The most commonly observed species and their probable stratigraphic sources are listed below:

Pelecypoda	Formation or Age
Anadara ovalis (Bruguiére)	Sangamonian
Anadara transversa (Say)	Sangamonian
Donax variabilis Say	Sangamonian
Exogyra costata Roemer	Peedee Formation
Glycymeris americana (Defrance)	Waccamaw Formation
Mercenaria campechiensis (Gmelin)	Sangamonian or Waccamaw Formation
Mulinia lateralis Say	Sangamonian or Waccamaw Formation
Noetia ponderosa (Say)	Sangamonian
Gastropoda	
Busycon contrarium (Conrad)	Sangamonian or Waccamaw Formation
Echinodermata	
Regularia spines	Sangamonian or Waccamaw Formation

DEPOSITIONAL ENVIRONMENT

It is apparent that strong current action was instrumental in the deposition of the "coquina" at 20th Avenue South, Myrtle Beach. This conclusion is strongly supported by the festoon cross-bedding and the presence of many cobbles and large, heavy abraded shells and shell fragments.

Water velocity sufficient to transport the material of the "coquina" could occur in a stream, an inlet, or in a longshore current.

If the "coquina" represents a stream deposit it would have to date from a period during the Pleistocene when the sea stood lower than at present, and the stream would have had to flow essentially parallel to the shore. If the stream deposit had pre-dated the Myrtle Beach Barrier Bar it would in all likelihood have been destroyed in the surf zone of the transgressing sea in which the Myrtle Beach Bar was later built.

If the stream deposit were younger than the Myrtle Beach Bar (i.e., post-Sangamonian) it is difficult to understand why it would not have flowed southeastward toward regional base level. It is equally difficult to understand where it could have come from in view of the lack of evidence of any such stream crossing the Myrtle Beach Bar at any point along its length between Myrtle Beach and the North Carolina line.

It is difficult to accept the idea of the "coquina" as an inlet deposit because (1) there is no evidence of any break in the Myrtle Beach Barrier Bar in the area, (2) the festoon cross-beds indicate a current flowing only in one direction, (3) an inlet would more likely be normal to than parallel to the northeast-trending shoreline, and (4) no source of pebbles and cobbles is known in the immediate area. A 75 foot power auger hole (26AH39) drilled into the Myrtle Beach Bar about 500 ft. inland from the beach at 20th Avenue South did not encounter the "coquina". Instead, it penetrated a fairly thick section of sands below the bar carrying an abundant fauna of the Pleistocene mollusks most typical of the surf zone.

It seems most likely to the authors that the materials of the "coquina" were transported to their present site by longshore currents. These currents flowed from the northeast essentially parallel to both the present shore and to the Pleistocene Myrtle Beach Barrier Bar. The sediments of the "coquina" could have been eroded from rock outcrops on the sea floor or could have been scoured off the floor and sides of inlets and carried to the sea by tidal currents where they were picked up by longshore currents and carried southwestward for many miles.

CEMENTATION

The cementing material of the "coquina" at 20th Avenue South Myrtle Beach, is crystalline calcite; and the rock is for the most part well indurated so that it breaks to a clean face when struck sharply with a hammer.

The calcite cement was probably derived from solution of shell material in overlying or surrounding sediments during a period of burial or subaerial erosion.

AGE

The Pleistocene age of the "coquina" at 20th Avenue South is established by its contained Pleistocene fossils and the stratigraphic position of the deposit. It must be essentially contemporaneous with or younger than the Myrtle Beach Barrier Bar because it would otherwise have been destroyed by the sea in which the bar was built. Its position overlying and lapping against the bar is also consistent with a contemporaneous or younger age.

If formed by longshore currents, as seems most probable, the "coquina" at 20th Avenue South could only have been deposited during or just after construction of the Myrtle Beach Barrier Bar in Sangamonian time or after the post-Wisconsin sea came back to its present stand. Because of the probability that burial or subaerial weathering was involved in the process of cementation of the "coquina", it is thought unlikely that induration of the rock occurred in the modern cycle (i.e., the present stand of sea level). The presence of the "coquina" within a foot or two of the high tide mark on the beach at 20th Avenue South is also evidence against deposition in the present day sea because the "coquina" was deposited by strong currents in water which must have been 5 to 10 feet or more deep and, therefore, at least 5 to 10 feet higher than the present sea level. This higher sea level best fits the concept of deposition in Sangamonian time as we do not as yet have good evidence in Horry County for a post-Wisconsinan sea higher than the present level.

In general, extensive drilling and surface studies by the authors in the area suggest the "coquina" at 20th Avenue South to be essentially contemporaneous with marine and lagoonal deposits exposed inland along the Intracoastal Waterway, which are judged to be Sangamonian in age (DuBar, 1962; and DuBar and Chaplin, 1963).

EFFECT ON BEACH EROSION

Observations made on September 24 and October 5, 1963, by the junior author showed the "coquina" outcrop on the beach at 20th Avenue South to have become largely covered by a buildup of sand so that only relatively small patches of the rock remained exposed, these being on the lower foreshore near the low water mark.

At low tide, plunging breakers undercut the "coquina" causing blocks of it to slump seaward. Incoming swell from the east-southeast causes waves which strike the N 50° E shore line at an approximate 30° angle of incidence, resulting in a steady longshore drift to the southwest (Fig. 2). The long curve of the beach to the northeast and southwest appears to be undergoing erosion. Only the immediate area of the "coquina" shows evidence of accretion. The area southwest of the "coquina" outcrop shows appreciably more erosion than other parts of the shore for a mile or so in either direction.

Apparently the "coquina" outcrop at 20th Avenue South acts as a barrier to southwestward longshore drift and causes local accretion. Erosion along the beach for several hundred yards southwest of the rock outcrop, therefore, is greater than normal because relatively little sand is being brought in to replace that taken away.

OTHER SIMILAR DEPOSITS

A number of "coquina" deposits similar to that at 20th Avenue South, Myrtle Beach, are known in North and South Carolina. Brief mention of these is made below. The authors visited several of the deposits but made no attempt at exhaustive studies.

Edisto Beach

A. J. Willis of the South Carolina Division of Commercial Fisheries and C. B. Stevens and G. R. Lunz of Bears Bluff Laboratories report "coquina" on the sea floor just off Edisto Island, Charleston County, South Carolina. The rock is in 12 to 17 feet of water about 2000 yards off the beach and extends from Frampton Inlet for about 4.5 miles southwestward in a long, narrow strip parallel to the N 50° E trending shore line. Trawlers working in the area are careful to avoid the strip of rock, and anchors and other gear are frequently lost there by unwary fisherman. A specimen supplied by G. R. Lunz is composed of shell fragments and fine to coarse grained pebbly sand, strongly cemented by calcium carbonate. The small quartz pebbles are rounded to subrounded, many of the shells appear worn, and the rock is strongly layered so that it resembles the cross-bedded "coquine" at 20th Avenue South, Myrtle Beach. The insoluble residue of the specimen submitted by Lunz was 66 percent by weight.

Murrells Inlet

Ben Heyward of the South Carolina Division of Commercial Fisheries provided information on "coquina" at Murrells Inlet, Georgetown County, South Carolina. He reports occurrences of cemented sand and shell at the Myrtle Beach Air Force Base marina and on the shore of Parsonage Creek, 0.3 mile southwest of the marine and 0.35 mile northeast of the Murrels Inlet Post Office.

Small specimens of the rock supplied by Heyward are a partly indurated mixture of sand and shell. The three samples examined are somewhat weathered and slightly leached. Generally the shell fragments are too poorly preserved for identification, but numerous valves of <u>Mulinia lateralis</u> were noted. The insoluble residues of three samples were 46.0, 36.5, and 22.0 percent by weight.

2nd Avenue North, Myrtle Beach

A bed of "coquina" is exposed at dead low water at 2nd Avenue North, Myrtle Beach, South Carolina. When visited by the authors on November 3, 1963, the tide was lower than normal and rock in place was exposed from about 100 feet northeast of the 2nd Avenue Pier to a point along the shore about 250 yards southwest of the pier. The patch of rock exposed was up to 200 feet wide and nearly all of it would be covered by water most of the time.

The lithology of this "coquina" is practically identical to the "coquina" at 20th Avenue South, even to the extent of containing large cobbles of quartz, phosphate rock, sandstone, and limestone. The surface of the exposure was rough and knobby, and no indication of crossbedding could be seen. This outcrop closely resembles the seawardmost part of the outcrop at 20th Avenue South, which also appears structureless. The insoluble residue of one sample from 2nd Avenue North was 58.5 percent by weight.

Prices Creek (Windy Hill)

Richards (1936, p. 1638) refers to "coquina" at Windy Hill and White Point Creek (Prices Creek) in Horry County, South Carolina. He cites C. W. Cooke (personal communication) and Pugh (1906) as the sources of his information, apparently not having visited the area. Pugh (1906) was obviously referring to Tuomey's earlier report (1848, p. 187), which states as follows:

"On Price's Creek, not far from this locality, a bed of loose, disconnected valves of shells occurs, which is six feet thick. The shells are not water-worn, but resemble the beds of shells thrown up by storms, on the shore. It is about half a mile from the beach, and is elevated above tide, five feet. The shells are principally _Venus mercenaria_, _Ostrea virginiana_, and _Arca incongrua_. I also found among them a West Indian _Arca_, and a species of _Pectunculus_."

Cooke (1936, p. 153-154) cites the Tuomey quote above and further states, "About 5 feet of coquina containing oysters and other bivalves is exposed on the north side of White Point Creek on United States Highway 17."

In November, 1963, the authors attempted to find the deposits mentioned above. Local inquiry and search in the area disclosed no "coquina" or thick shell beds on Windy Hill Beach or exposed in the banks of White Point Creek, which merges in the vicinity of U. S. 17 with Prices Creek in the area between the highway and the Intracoastal Waterway. Cooke's 5 feet of "coquina" on the north side of White Point Creek on U. S. 17 is apparently no longer exposed. The authors did, however, find a 6 foot thick remnant patch of shell hash, underlain and overlain by fine to medium sand, in a sand pit (Loc. 26-15) on the west edge of Price's Creek, 0.22 mile N 76° W of the U. S. 17 bridge over Prices (or White Point) Creek. This deposit consists of roughly equal amounts of fine to medium sand and buff colored shell fragments and small whole shells. The insoluble residue of a typical sample was 36.0 percent by weight. The most common mollusk species are listed below:

Pelecypoda	Gastropoda
Anadara ovalis (Bruguiére)	_Crepidula fornicata_ (Linné)
Anadara transversa (Say)	_Nassarius obsoletus_ (Say)
Arca zebra Swainson	_Oliva sayana_ Ravenel
Crassostrea virginica (Gmelin)	
Donax variabilis Say (abundant)	
Mulinia lateralis Say (abundant)	
Tagelus plebeius (Spengler)	

The deposit appears to represent a storm or surf zone accumulation of shell and is probably part of the Myrtle Beach Barrier Bar (Sangamonian). The deposits reported by Tuomey and Cooke in this same area are probably similar accumulations.

A power auger hole (26AH69) drilled by the authors on the south side of U. S. 17 at a point 1/2 mile southwest of its crossing of Prices Creek encountered similar sandy calcareous shell hash at an elevation of 7 to -10 feet (msl). This is part of the Myrtle Beach Barrier Bar (Sangamonian). Because of the lack of induration, neither this material nor the occurrences mentioned above qualify as "coquina".

Fort Fisher

"Coquina" crops out along several hundred yards of beach in an area about 2000 feet north of old Fort Fisher, New Hanover County, North Carolina. The rock is strongly cemented by calcium carbonate and is predominantly medium to very coarse sand and shell fragments with sparse rounded quartz and phosphate rock pebbles up to about 2 inches in diameter. The insoluble residue of one sample was 35.5 percent by weight. Stevenson (1912, p. 288) reports the presence of "Fulgur carica, Ostrea virginica, Venus mercenaria, Rangia cuneata," identified by T. Wayland Vaughan. Richards (1950, p. 44) reports the presence also of Noetia ponderosa, Venericardia tridentata, Donax variabilis, and Mulinia lateralis.

Well developed festoon cross-beds (Fig. 5) are the dominant sedimentary structure of the Fort Fisher "coquina". The troughs of these are 1 to 3 feet, 10 to 20 feet wide, and 20 feet or more long. Trough axes trend S 10° E to S 30° W and have an average trend of about due south. Individual cross-strata dip up to 35°, all dips being in a southward direction. The strand line here trends approximately N 15° E.

It is apparent that the Fort Fisher "coquina" was deposited by a strong southward-flowing current, as was the "coquina" at 20th Avenue South, Myrtle Beach. The Fort Fisher deposit is also in the same relative position on the seaward edge of a barrier beach. A southward-flowing longshore current in the Fort Fisher area today carries sand along the beach and piles it up on the "coquina" outcrop. The beach south of the "coquina" outcrop is undergoing vigorous erosion, and much of old Fort Fisher has already been destroyed.

In its effect on local beach accretion and erosion, and in its whole general aspect, the Fort Fisher "coquina" is much like the "coquina" at 20th Avenue South, Myrtle Beach.

Kure Beach

U. S. Coast and Geodetic Survey Chart 1235 shows an irregularity

Figure 5. "Coquina" at Fort Fisher, New Hanover County, North Carolina, showing well developed festoon cross-bedding.

in the strand line at Kure Beach, New Hanover County, North Carolina, that suggests local accretion and erosion similar to that caused by "coquina" at 20th Avenue South, Myrtle Beach, and at Fort Fisher. The authors walked several hundred yards of beach here at low tide on November 2, 1963, but found no rock in place. Scattered fragments and rough cobbles of "coquina" and peat were present on the beach, and the operator of the pier at this point stated that "rocks" were present along the bottom a hundred feet or so offshore and that rock had been encountered at a depth of 18 feet in driving the piles for the pier. It is possible that "coquina" is present here but is not exposed by normal tides or has been covered by local accretion.

A specimen of "coquina"-like material found by the authors on the beach here had an insoluble residue of 15.0 percent by weight. This rock, presumably thrown up on the beach by waves, was quite hard, dense, and sandy and contained scattered, small unidentifiable shell fragments.

Carolina Beach

Stevenson (1912, p. 288-289) reports an outcrop of "coquina" at Carolina Beach, North Carolina, as follows:

> "From a similar (to the "coquina" at Fort Fisher) Pleistocene coquina bed 1 mile southeast of Carolina Beach wharf in southern New Hanover County, Dr. Vaughan also collected and determined the following forms: Arca ponderosa, Arca petaxa, Ostrea virginica, Venus mercenaria, Rangia cuneata and Spisula solidissima."

The "coquina" referred to by Stevenson may be the same as the suspected occurrence at Kure Beach. The authors did not make an exhaustive search in the area.

Snows Cut

Clifflike exposures of "coquina" are present in the banks of the Intracoastal Waterway at Snows Cut, about a mile northwest of Carolina Beach, New Hanover County, North Carolina. The rock is cemented by calcium carbonate and consists of coarse to very coarse sand, fine rounded quartz gravel, fine broken shell fragments, and heavy whole shells of such species as Mercenaria campechiensis, Crassostrea virginica, and Rangia cuneata. Most of the large whole shells are worn and are convex upward. The rock is strongly cross-bedded (Fig. 6) in small to medium scale sets roughly half of which dip eastward and half westward. A sample from the lower part of the "coquina" section yielded an insoluble residue of 83.0 percent by weight, and the insoluble residue of a similar sample from higher in the "coquina" was 47.0 percent by weight.

The coarse debris, the worn character of many of the large whole shells, and the east-west cross-bed dips suggest deposition in a strong current that flowed in alternate directions, such as might be found in an inlet or across a low underwater bar.

Gander Point

Richards (1936, p. 1635) reports abundant shell fragments and "coquina" in a gravel pit at Gander Point, between Wilmington and Carolina Beach, New Hanover County, North Carolina.

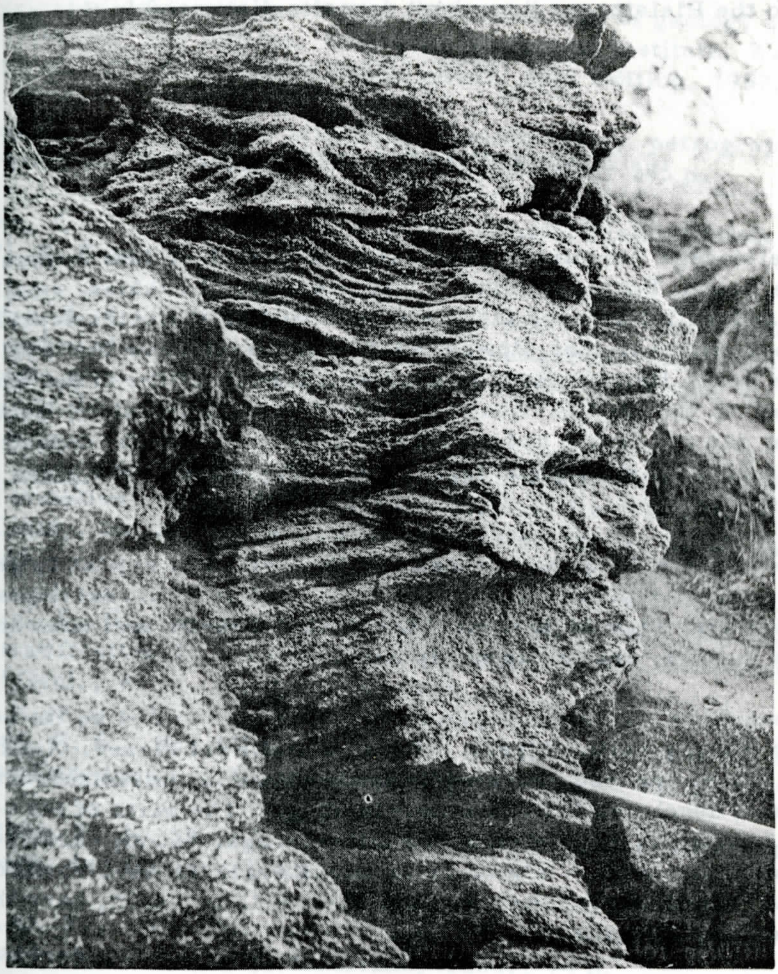

Figure 6. Cross-bedding in "coquina" at Snows Cut, New Hanover County, North Carolina. (Canoe paddle for scale).

Beaufort - Cape Hatteras Region

Wells and Richards (1962) have discussed "coquina" occurrences in 30 to 40 feet of water offshore in the Beaufort - Cape Hatteras region, North Carolina. They list 73 species of invertebrate fauna from the "coquina" and conclude that the deposits are Sangamonian in age and that they are similar to the Anastasia Formation of Florida and to the "coquina" at Myrtle Beach and Fort Fisher.

A "reef" studied by Pearse and Williams (1951, p. 133) several miles off the mouth of New River Inlet, North Carolina, was found to have a base of "Trent Marl" (Miocene) and thus apparently is not related to the Pleistocene "coquina" deposits discussed in this paper.

SUMMARY AND CONCLUSIONS

Pleistocene "coquina" crops out on the beach at 20th Avenue South, Myrtle Beach, South Carolina. The presence of cobbles, small boulders, and well developed festoon cross-bedding indicates deposition by a strong current that flowed southward parallel to the Pleistocene Myrtle Beach Barrier Bar. Contained fossils, position of the "coquina" relative to the Myrtle Beach Barrier Bar (Sangamonian), relation to present day sea level, and similarity to other "coquina" deposits along the Carolina coast indicate deposition most probably took place during Sangamonian time.

Pleistocene "coquina" deposits of the Carolinas appear to group in three general types. These are (1) longshore current deposits on the seaward edge of barrier bars, (2) storm or surf zone accumulations in bars, and (3) inlet deposits.

Longshore current "coquina" deposits are typified by the outcrops at 20th Avenue South, Myrtle Beach, and at Fort Fisher, North Carolina. Where exposed above water these deposits characteristically exhibit well developed festoon cross-bedding. The parts of the outcrops that are only rarely above water have a rough, knobby surface and appear structureless. These parts are thought to have formed under similar conditions, however, and may well in reality have the same sedimentary structures.

Cementation of the "coquina" deposits probably took place at a time of lower sea level when weathering of the shelly sands caused solution and redeposition of calcium carbonate.

Other "coquina" deposits may be present in association with ancient offshore bars at higher levels in the Coastal Plain.

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CHEMICAL ANALYSES OF ROCKS

OF THE CAROLINA SLATE BELT

by

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ABSTRACT

Five new analyses of phyllite, silicified argillite, amygdaloidal greenstone, vitric-crystal tuff and volcanic breccia were made from rocks of the Carolina slate belt in Orange County, North Carolina. The phyllite is probably a metamorphosed argillite. Chemical composition of the greenstone is similar to Nockold's average "central" basalt. The vitric-crystal tuff and volcanic breccia are chemically similar to one another and to the average for rhyodacite and for graywacke.

About 65 chemical analyses from the Carolina slate belt have been published previously, but many of them are incomplete or were made from weathered samples. Volcanic rocks in the belt are probably calc-alkalic and range in composition from basaltic to rhyolitic. Dacite apparently is the most common volcanic rock and argillite the most common rock of known sedimentary origin.

INTRODUCTION

Low-rank metamorphic rocks, probably of Paleozoic age, crop out in the Carolina slate belt, which extends about 400 miles from south central Virginia to central Georgia (Tectonic Map of the United States, 1962). The exposed part of the belt has a width of about 50 miles in the Piedmont of central North Carolina. Rocks in the Carolina slate belt include argillite, slate, phyllite, tuff, sandstone, conglomerate, breccia and greenstone. Rocks such as amygdaloidal and vesicular greenstone and vitric-crystal tuff are of volcanic origin;

others such as laminated argillite and quartz pebble conglomerate are of sedimentary origin. However, it is difficult to determine whether many of the rocks are volcanic or sedimentary, because of lack of diagnostic features. The composition of the volcanic rocks ranges from rhyolitic to basaltic, but most of them are probably dacitic and andesitic. Most of the rocks show evidence of metamorphism, and mineral assemblages generally are indicative of the chlorite zone of regional metamorphism.

The geology of the slate belt has been reviewed by King (1955) and Stuckey and Conrad (1958). Several recent reports have been published (Conley, 1962a, 1962b; Parker, 1963; Sundelius, 1963).

The writer has been working intermittently in the Carolina slate belt since the spring of 1962. A preliminary report on the rocks of Orange County, North Carolina was published in this journal (Butler, 1963). The purpose of this paper is to present five new chemical analyses from Orange County and to review the chemical composition of rocks of the Carolina slate belt as indicated by published analyses.

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CHEMICAL ANALYSES FROM ORANGE COUNTY

Rocks of Orange County

Orange County is situated approximately in the middle of the main exposed part of the Carolina slate belt in north-central North Carolina. Most of the county is underlain by metamorphosed volcanic and sedimentary rocks intruded by plutons of diorite, tonalite, granodiorite, and adamellite. Composition of the intrusive rocks is not considered in this report. The volcanic and sedimentary rocks are mainly of the following types: (1) argillite, (2) slate and phyllite derived from argillite or from tuffaceous deposits, (3) clastic rocks composed mainly of subangular to subrounded lithic clasts up to 2.5 feet in size, probably representing volcanic debris reworked in part by sedimentary processes, (4) devitrified vitric-crystal tuff, and (5) greenstone, which is amygdaloidal and vesicular in some localities.

Samples were taken at 35 localities and 53 thin sections prepared; five samples were chosen for chemical analysis.

Phyllite

The sample was obtained from fresh rock dug up during construction of a power line crossing N. C. Highway 86 at Old Field Creek, 4.6 miles north of Chapel Hill town hall. The rock is an aphanitic, greenish gray phyllite with good slaty cleavage. Specks of a sulfide, probably pyrite, are present along healed fractures. Adjacent outcrops have good slaty cleavage (N 55° E, 84° NW).

The texture is lepidoblastic and average grain size is less than .05 mm. Constituent minerals are sericite and quartz, with minor amounts of pyrite and calcite.

The chemical composition (Table 1, Column 1) suggests that the original rock was composed mainly of quartz and clay minerals, either a mudstone or a siltstone. The rock is more siliceous than averages for shale quoted by Pettijohn (1957, p. 344) and is somewhat similar to average Mississippi delta sediment (Pettijohn, 1957, p. 344, Column F) and a Precambrian argillite from Michigan (p. 345, Column E). Sulfur content of the phyllite is abnormally high and may indicate that some metasomatism occurred.

Silicified Argillite

Large residual boulders of a flinty aphanitic rock occur on county road No. 1777, 150 yards W. of N. C. Highway 86, 2.6 miles north of Chapel Hill town hall. Sample taken from the boulders is medium bluish gray on fresh surfaces and has a yellowish gray weathered rind about one cm. thick. The rock is cut by thin (up to one mm.) veins of clear quartz. The sample is difficult to break and has sub-conchoidal fracture.

Grain size is too small for most minerals to be identified by microscope. However, recognizable grains of epidote, chlorite, and quartz are present. An x-ray pattern of the rock indicates that quartz, feldspar, and chlorite are the major minerals.

The chemical composition (Table 1, Column 2) is much like that of

Table 1. Chemical analysis of phyllite, silicified argillite, greenstone, and basalt. Analyses 1-3 were made by Technical Service Laboratories, Toronto, Ontario.

	1.	2.	3.	4.
SiO_2	72.04	57.44	47.48	51.33
TiO_2	0.32	0.94	0.52	1.10
Al_2O_3	14.12	16.89	20.42	18.04
Fe_2O_3	2.21	0.96	6.41	3.40
FeO	0.65	7.10	3.61	5.70
MnO	0.04	0.30	0.22	0.16
MgO	1.05	4.86	4.53	6.01
CaO	1.08	3.10	10.52	10.07
Na_2O	0.18	3.70	2.00	2.76
K_2O	4.00	1.36	2.30	0.82
H_2O^+	1.29	2.66	1.65	0.45
H_2O^-	0.01	0.04	0.03	-
P_2O_5	n.d.	n.d.	n.d.	0.16
CO_2	0.24	0.10	0.11	-
S	1.51	0.02	0.03	-
	98.74	99.47	99.83	100.00

1. Phyllite, No. OC-19A.
2. Silicified argillite, No. OC-40.
3. Amygdaloidal greenstone, No. OC-28C.
4. Average of 56 "central" basalts, Nockolds, 1954, p. 1021.

a silt from a varved sediment of Finland (Pettijohn, 1957, p. 345, Column A).

Field relationships and petrography yield no diagnostic criteria of origin. At other localities in the slate belt, the writer has seen laminated argillites with well-preserved bedding and a similar hard, flinty nature. It seems most likely that this rock is a massive argillite that has undergone silicification.

Greenstone

Greenstone occurs in boulders and outcrop along county road No. 1723, 0.3 mile W. of N.C. Highway 86, 7.9 miles N. of Chapel Hill.

It is a fine-grained, grayish green rock with no obvious layering or cleavage. Small clots one to two mm. in diameter of yellow green epidote and dusky green chlorite are scattered throughout the rock. Quartz amygdules up to 3 cm. in longest dimension are common at this locality. Vesicles, as well as amydules, are present in the greenstone at other localities.

Constituent minerals are epidote, chlorite, sericite, quartz, actinolite, and opaques. Albite, which is present in other samples from this locality, may occur in grains too small to identify.

In Table ~~2~~ 1, composition of the greenstone (Column 3) may be compared with Nockolds' average "central" basalt (Column 4). The major differences are the abnormally high alumina and potash in the greenstone, which may be the result of metasomatism or metamorphic differentiation that caused formation of sericite.

The chemical composition and the presence of amygdules suggest that the greenstone is a metamorphosed basalt flow.

Devitrified Vitric-crystal Tuff

The vitric-crystal tuff crops out in the roadcut along N. C. Highway 86, 0.7 mile N. of intersection with country road No. 1723 and 8.3 miles N. of Chapel Hill. It is an aphanitic rock with a distinctive fragmental structure (Butler, 1963, p. 178-180). The fragments, which make up about 40% of the rock, are roughly lenticular in shape and attain a maximum size of about one by six inches. Scattered plagioclase crystals are present in both fragments and groundmass.

Plagioclase (generally of oligoclase composition), epidote, chlorite, quartz, sericite, and calcite can be identified in thin section. A pronounced banding is present and the bands bend around crystal and lithic clasts in a manner suggesting considerable compaction. Both the lenticular structures and microscopic texture resemble features described in welded tuffs. The lenticular structures could be collapsed pumice fragments.

Aphanitic rocks of similar general appearance but without the lenticular structure occur in several other localities. Spherulites and vitroclastic texture are present in these rocks. These features suggest that many of the tuffs contained a significant proportion of volcanic glass. The analysed specimen has an estimated composition of 85% devitrified glass, 10% plagioclase crystal clasts, and 5% lithic clasts.

Table 2. Chemical analyses of vitric-crystal tuff, volcanic breccia, rhyodacite, and graywacke. Analyses 1 and 2 were made by Technical Service Laboratories, Toronto, Ontario.

	1.	2.	3.	4.
SiO_2	64.54	65.43	66.27	64.7
TiO_2	0.67	0.50	0.66	0.5
Al_2O_3	13.13	12.54	15.39	14.8
Fe_2O_3	2.25	2.96	2.14	1.5
FeO	5.01	3.86	2.23	3.9
MnO	0.13	0.16	0.07	0.1
MgO	1.18	1.35	1.57	2.2
CaO	2.81	4.08	3.68	3.1
Na_2O	4.18	4.14	4.13	3.1
K_2O	2.99	1.98	3.01	1.9
H_2O^+	1.12	1.18	0.68	2.4
H_2O^-	0.02	0.02	-	0.7
P_2O_5	n.d.	n.d.	0.17	0.2
CO_2	0.69	0.88	-	1.3
S	0.22	0.12	-	0.2
SO_3	n.d.	n.d.	-	0.4
	98.94	99.20	100.00	101.0

1. Vitric-crystal tuff, No. OC-18A.
2. Volcanic breccia, No. OC-38.
3. Average of 115 analyses of rhyodacite and rhyodacite-obsidian, Nockolds, 1954, p. 1014.
4. Average of 23 analyses of graywacke, Pettijohn, 1957, p. 307, Column A.

The chemical composition (Table 2, Column 1) is similar to the average rhyodacite and rhyodacite-obsidian (Table 2, Column 3) of Nockolds (1954, p. 1014). The major difference is in the alumina and ferrous oxide.

Volcanic Breccia

Volcanic breccia is one of the most common rock types in Orange County. The sample analysed was taken from boulders blasted during roadbuilding along county road No. 1006 between Hillsboro and Orange Grove, 0.9 mile S. of Cross Roads Church and 8.9 miles N.W.

of Chapel Hill. The general color of the rock is medium bluish gray, and it is composed of aphanitic lithic clasts ranging in color from dark gray to light greenish gray and white feldspar crystals up to 2 mm. in size. The lithic clasts are subrounded to angular and range in size up to 8 cm. At other localities in the county, the clasts are more than 2 feet in size. The rock is unsorted and has no visible bedding planes. Nearly all of the lithic clasts are aphanitic igneous rocks, and some are porphyritic. Some clasts may be argillite, but clasts of phaneritic rocks are very rare.

Plagioclase, sericite, chlorite, epidote, calcite, quartz, and opaque minerals can be observed in thin section. The plagioclase is mostly oligoclase and some clasts are zoned. Lithic clasts make up about 52% of the rock, crystal clasts 18%, and groundmass 30%.

There is a close correspondence of the composition of the volcanic breccia (Table 2, Column 2), to that of the vitric-crystal tuff (Column 1). Both are similar to Nockolds' average rhyodacite (Column 3) and Pettijohn's average graywacke (Column 4). A comparison of graywacke analyses quoted by Pettijohn (1957, p. 306-307) with average igneous rocks of Nockolds (1954) illustrates that graywackes are generally similar in composition to rhyodacite or dacite (extrusive equivalents of granodiorite and tonalite, respectively) and that Na_2O is greater than K_2O in graywackes, almost without exception. It is possible that the volcanic breccia is a sedimentary rock of the graywacke suite, composed mainly of reworked volcanic material. Parker (1963) has emphasized the importance of the graywacke suite in the Carolina slate belt.

REVIEW OF CHEMICAL ANALYSES FROM THE CAROLINA SLATE BELT

General Remarks

More than 65 chemical analyses of rocks and minerals from the Carolina slate belt have been published of which more than half are from North Carolina.

The purpose of this section is to discuss the chemical characteristics of rocks of the slate belt. The major papers were reviewed, but no exhuastive search of the literature was made. The writer attempted to select analyses that the original author thought was representative of rock units, and not obviously weathered or hydrothermally altered. About 45 analyses meet the above criteria and more than half of these are from North Carolina. Parts of the slate belt represented and references are as follows:

(1) Virgilina district, Virginia and North Carolina (Laney, 1917).
(2) Deep River area, North Carolina (Stuckey, 1928).
(3) Albemarle-Denton area, North Carolina (Pogue, 1910; Laney, 1910; Conley, 1962a, 1962b; Councill, 1954).
(4) South Carolina: Edgefield-Chesterfield zone of Sloan extending across the lower Piedmont from North Carolina to Georgia (Sloan, 1908; McCauley, 1961).
(5) Georgia: Little River series (Crickmay, 1952).

There is no good way to check on the accuracy of the published analyses and chemical trends not based on close comparison of analyses are open to question. One test of reliability is to see if similar trends are present in data from different areas and from different analysts. The conclusions below should be considered tentative until they are verified or disproved by later work.

Alkali-lime Index

The alkali-lime index (Peacock, 1931) is a useful way of characterizing a series of igneous rocks. Total alkalies ($Na_2O + K_2O$) and lime (CaO) are plotted against silica (SiO_2). The percentage of silica at which alkalies and lime are equal is called the alkali-lime index. Four subdivisions are set up: alkalic (index less than 51), alkali-calcic (51-56), calc-alkalic (56-61), and calcic (greater than 61). Igneous rock series in the major orogenic belts of the world are calc-alkalic or calcic. Rock series in non-orogenic environments are commonly alkalic.

Twenty analyses of probable igneous rocks from the Carolina slate belt were used to determine the alkali-lime index (Fig. 1). Lime shows a fairly consistent trend, but there is considerable scatter in the values for alkalies. The four analyses of highest silica, which are rhyolites and felsic tuffs from the Albemarle area (Conley, 1962a, p. 12), are abnormally low in alkalies and apparently have been altered. The curve for alkalies as drawn in Figure 1 gives an alkali-lime index of 59, in the calc-alkalic range. The scatter of the points makes it hard to determine the best position of the curve for alkalies, but most alternate positions give an index in the 56-61 range.

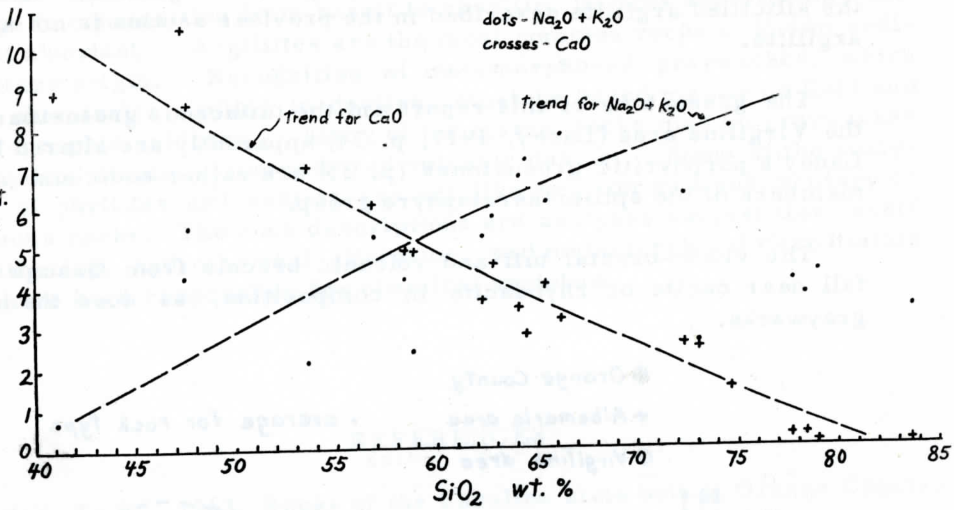

Figure 1. Plot of lime and total alkalies against silica. Twenty analyses of rocks of probable igneous origin are plotted. Trends as drawn in the figure intersect at 59% SiO_2, in the calc-alkalic range.

Variation in Silica and Alkalies

Many of the analyses were plotted in a diagram of silica against the ratio of potash to total alkalies (Fig. 2). In general, the effect of weathering should be an increase in both of these values. Therefore, sedimentary rocks derived by weathering and redeposition of calc-alkalic igneous rocks should generally lie above the line connecting averages for the igneous rocks (dotted line, Fig. 2). Analyses of spilites and keratophyres, which are characterized by a high content of Na_2O and low K_2O (Turner and Verhoogen, 1960, p. 260), would in most cases plot below the dotted line. Coincidence of two points on Figure 2 does not necessarily mean that the two rocks are chemically similar and the complete analyses must be compared before drawing conclusions about origin.

It is hard to evaluate accurately the effects of recent weathering. For example, several of the analyses given by Sloan (1908, p. 262-264) have very high values for alumina and loss of weight on ignition, and low values for alkalies, which suggests the presence of kaolinite.

The phyllite from Orange County, argillite ("bluestones") from Davidson County (Councill, 1954, p. 13), and felsic tuffaceous argillite and argillite from the Albemarle area (Conley, 1962a, p. 12) have compositions similar to published averages for argillites. However, the silicified argillite described in the previous section is not a typical argillite.

The greenstone of this report and the tuffaceous greenstones from the Virgilina area (Laney, 1917, p. 34) apparently are altered basalts. Laney's porphyritic greenstones (p. 33) are rather sodic and could be members of the spilite-keratophyre group.

The vitric-crystal tuff and volcanic breccia from Orange County fall near dacite or rhyodacite in composition, as does the average graywacke.

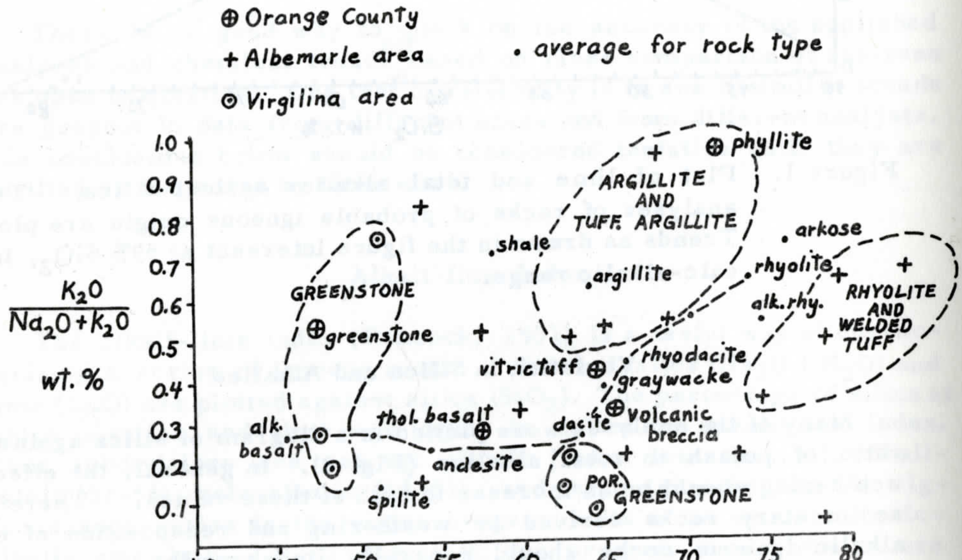

Figure 2. Plot of the ratio potash to total alkalies against silica. Values for average rock types are from Nockolds (1954) and Pettijohn (1957), except for argillite, which is from Reed (1957). Silicified argillite from Orange County is not labeled.

CONCLUSIONS

Chemical analyses from Orange County are from metamorphosed argillites, basalt flows, and unweathered volcanic rocks of rhyodacitic composition.

The volcanic rocks of the Carolina slate belt are calc-alkalic and range in composition from basalt to rhyolite. Dacites are probably the most abundant. Argillites are the most common rocks of known sedimentary origin. Recognition of metamorphosed graywackes, which are chemically similar to dacites, must be based mainly on field and petrographic evidence. Many of the clastic rocks may be graywackes composed mainly of unweathered volcanic debris. Some of the analyses of phyllites and schists are not like any common sedimentary or igneous rocks. The rock descriptions and analyses suggest that recent weathering, hydrothermal alteration, and metamorphic differentiation all have been responsible for chemical variation.

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FILLED SUBMARINE SPRING VENTS IN

CRETACEOUS ROCKS OF ALABAMA

by

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ABSTRACT

Sand-filled cones in a Cretaceous shale in Alabama are thought to be submarine spring vents, developed simultaneously with clay accumulation in a shallow sea. A model sub-aqueous spring produced similar cone-shaped openings. The scalloped outline of the funnels, in both the models and in Cretaceous rocks, appears to be due to the fact that "bubbles" of the lighter fluid rise in a tripartite vortex system.

* * *

Sandstone exposed along U.S. 231, about one mile south of Orion, Pike County, Alabama, is characterized by funnel-shaped protuberances into the underlying shale (Figure 1). These occur in several sizes, the largest being tens of centimeters across and a meter or more high. Each sandstone protuberance is made up of quartz grains thoroughly cemented with iron oxide. The contact between the sandstone, in the funnel, and the adjacent shale, is roughly conical, but not smoothly so: the curvature of the contact, at most places, is sharper than would be necessary to produce the cone shape. In cross-section, the outline of the contact has, therefore, a scalloped appearance. The shale close to each funnel is a light gray, whereas most of the shale is dark gray.

Both sandstone and shale are thought to be parts of the Providence Formation, of Cretaceous age.

No fossils or fossil fragments could be found. In order to make the search for fossils meaningful, the shale was disaggregated in a commercial petroleum-base cleaning agent, and selected fractions were examined under a binocular microscope. Flotation yielded no specimen. The environment of deposition must, therefore, be inferred from non-paleontologic evidence.

X-ray study showed that kaolinite is the dominant clay mineral in both the light and dark shales. (No mineralogic difference could be detected between the two shales.) This finding is taken as evidence that a near-shore, or transitional, depositional site is indicated. Field

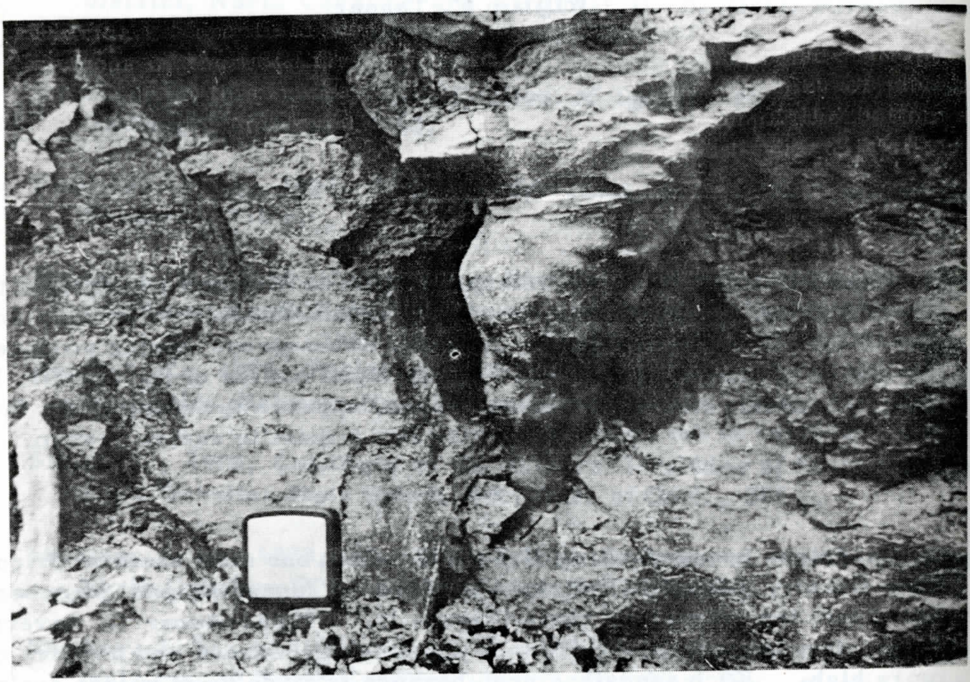

Figure 1. Detail of one sand-filled funnel, photographed in the field. The tape case (two inches on each side) is included for scale. The black patch is a hole, dug behind the funnel, to confirm a roughly circular cross-section. Bedding within the funnel is local convex down-ward, locally crumpled or slumped.

study of a number of funnels, well-exposed in vertical highway cuts, eliminated the possibility that these might be clastic dikes.

The following series of events was deduced from the field work:

1. Deposition of clay in a shallow, near-shore environment.
2. Development of cone-shaped openings through which ground water could escape upward.

3. Filling of the funnels, simultaneously with deposition of a sheet of quartz sand.
4. Ultimate cementation.

The first two steps probably overlapped in time; that is, the clay deposit may have accumulated around submarine springs while they were active in a low-energy coastal area.

To test this idea, a laboratory model was designed and operated. In this, a vent for compressed air was placed at the center of the bottom of the test vessel, which was filled with water. Air flow was adjusted until a relatively quiet bubbling regime was established. The air was selected to model fresh water, whereas tap water was used to model sea water. The density differences should be significant only in controlling the rate of flow and of mixing or dissipation; the rate of flow was modelled by altering air pressure, but no program was adopted for modelling mixing of spring water with sea water.

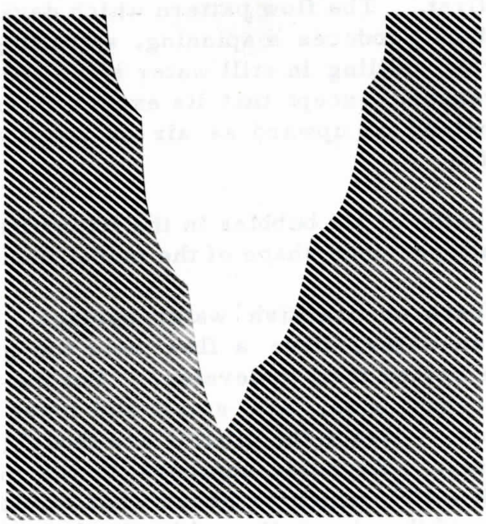

Figure 2. Representative outline of funnel. The laboratory model was about 10 cm high, and only a few centimeters wide at the top; field examples were larger than this, up to a maximum of about one meter high. The apical angle was typically close to 30°. Model funnels were empty cones in a clay base; those seen in the field were sandstone protuberances into a kaolinite shale.

After the model was operating in what appeared to be a satisfactory manner, dry, powdered clay was introduced slowly over a period of several days. When enough clay had been added to produce a layer about 10 cm thick, the model was allowed to operate for several additional weeks without tampering. Air pressure was not altered during any one model run.

After dehydration of any one model, the scalloped funnel was easy to observe. In each case it was a tiny replica of the funnels seen in the field, except that it was empty. Introduction of loose sand, and cementation with iron oxide, would have completed the picture.

During operation of the model, individual air bubbles rose from the bottom in a systematic fashion. The paths which they followed can be described best in terms of the tripartite vortex trail which develops behind a settling balloon, leaf, small pebbles, or sand grain. That is, detachment of a single air bubble sets up a flow pattern in the water so that the next bubble would be detached at about 120^{o} around an imaginary circle which enclosed the air vent. The third bubble commonly broke away halfway around the longer arc between the first two, and the fourth bubble was detached at approximately the same point as the first. The flow pattern which develops in the water under such conditions produces a spinning, spiralling motion by each air bubble. A grain settling in still water spins and spirals for precisely the same reason, except that its excess mass requires that it move downward instead of upward as air or fresh water does in sea water (Tanner, 1963).

The spiralling paths of air bubbles in the tripartite vortex trail accounted for the scalloped cone shape of the model funnels.

Large known fresh or brackish water springs, bubbling upward through shallow sea-water, have a flow rate too great for a single clear-cut tripartite vortex trail to develop. But the funnels reported here, from Cretaceous beds, are small and must have had rather restricted flow rates. Hence the models are thought to represent the prototypes accurately. Reynolds numbers in the model were in the range, $R = 10^2$ to $R = 10^3$, which is about what would be expected for fresh water springs of the size indicated by the funnels. The Froude number is not critical in either case.

The model ratio of length could be computed at $\lambda = 1$ for the smaller funnels, or perhaps as small as $\lambda = 0.05$ for the largest funnels. In view of the relatively slight departure from unity, the length factor is thought not to be critical.

The conclusion is drawn, therefore, that the sandstone funnels are probably sand-filled submarine spring vents which developed in a shallow, near-shore part of the late Cretaceous sea. This result is consonant with general late Cretaceous paleogeography of the area (Tanner, 1962).

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